Materials and Design 32 (2011) 1651–1656

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Technical Report

Developing Temperature–Time and Pressure–Time diagrams for diffusion bonding AZ80 magnesium and AA6061 aluminium alloys

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ARTICLE INFO

Article history:
Received 26 June 2010
Accepted 11 October 2010
Available online 14 October 2010

ABSTRACT

The principal difficulty when joining magnesium (Mg) and aluminium (Al) lies in the existence of formation of oxide films and brittle intermetallic in the bond region. However diffusion bonding can be used to join these alloys without much difficulty. In this investigation, an attempt was made to develop Temperature–Time and Pressure–Time diagrams for diffusion bonding of AZ80 magnesium (Mg) and AA6061 aluminium (Al) dissimilar materials. The bonding quality of the joints was checked by microstructure analysis and lap shear tensile testing. Based on the results Temperature–Time and Pressure–Time diagrams were constructed. These diagrams will act as reference maps for selecting appropriate diffusion bonding process parameters to join AZ80 magnesium alloy and AA6061 aluminium alloy without trial experiments.

1. Introduction

Magnesium (Mg)–aluminium (Al) alloys have good features such as low density, good damping characteristics, dimensional stability, machinability and low casting costs and hence recently attracted greater attention in academic research and industrial applications [1]. The research and application of Mg and Al alloys have been extended from navigation and military fields to civil products of high additional value such as automobile, computer and communication equipments. Dissimilar welding of Mg and Al alloys would achieve weight reduction and high efficiency of production by substitution of Mg and Al alloys for steels [2].

However, the refractory oxide film of Mg and Al results in inclusions at the weld metal. Moreover, the conventional fusion welding technique causes severe thermal cracking and easy formation of brittle intermetallics in the joints produced. Therefore the welding of Mg and Al dissimilar materials by the fusion welding method is very difficult [3]. Hence, the researchers recommend diffusion bonding technique to join these dissimilar materials. The selection of diffusion bonding process variables affecting the interfacial structure, compound formation and morphology is critical to attain good quality bonds [4].

The predominant process parameters in diffusion bonding process are: (bonding) temperature, (bonding) pressure and (holding) time [5]. From the literature review, it is understood that the reported literature [6–9] on diffusion bonding of Mg–Al dissimilar materials could be counted with fingers. Moreover, those literatures are focusing on microstructure analysis, phase formation studies, hardness survey at the interface and their subsequent influence on bonding strength. Mahendran et al. [10] developed diffusion bonding windows for joining AA2024 aluminium and AZ31B magnesium alloys. However, no literature was found on constructing Temperature–Time (T–t) and Pressure–Time (P–t) diagrams for joining Mg–Al dissimilar materials. Hence, the present investigation was carried out to construct T–t and P–t diagrams for joining two important alloys, namely AZ80 magnesium alloy and AA6061 aluminium alloy and the details are presented in this paper.

2. Experimental work

Square shaped specimens (50 mm × 50 mm) were machined from rolled plates of 10 mm thick magnesium (AZ80) and 6 mm thick aluminium (AA6061) alloys. The chemical composition of the base metals used in this investigation is shown in Table 1. The bonding surfaces of samples were ground flat by 200#, 400# and 600# grit SiC papers and cleaned in acetone prior to diffusion bonding [11]. Then the polished and chemically treated specimens were stacked in a die made up of 316L stainless steel and the entire diffusion bonding setup, shown in Fig. 1, was inserted into a vacuum chamber (vacuum pressure of −29 mm Hg was maintained).

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doi:10.1016/j.matdes.2010.10.011

Table 1
Chemical composition of base metals.

	Mg	Si	Ti	Cr	Mn	Fe	Cu	Zn	Pb	Sn	Zr	Al
AA6061	1.0	0.5	0.15	0.1	0.15	0.7	0.2	0.25	–	–	–	Bal.
AZ80	Bal.	–	–	–	0.101	–	–	0.398	0.005	0.001	Traces	8.140

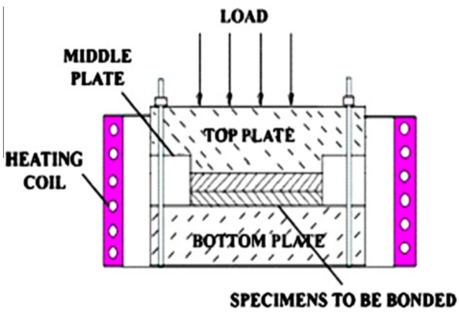


Fig. 1. Configuration of the diffusion bonding setup.

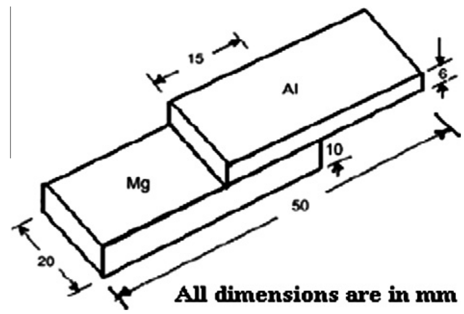


Fig. 3. Dimensions of lap shear tensile test specimen.

The specimens were heated up to the bonding temperature using induction furnace with a heating rate of 25 °C/min, simultaneously the required pressure was applied. After the completion of bonding, the samples were cooled to room temperature before removal from the chamber. By this procedure, 35 joints were fabricated using different combinations of bonding temperature, bonding pressure and holding time and they are displayed in Fig. 2. Microstructure analysis was carried out using a light optical microscope to check the formation of diffusion layer at the interface. The magnesium side was etched with a solution containing ethanol, picric acid, acetic acid and water whereas the aluminium side was etched with Keller's solution. As the joints were not large enough for normal lap shear testing, a non-standard test was devised to measure the shear strength of the bonds. The dimensions of lap shear tensile test specimen are shown in Fig. 3 and these specimens were prepared from the Mg/Al diffusion bonded joints by a line cutting machine (electric spark cutting). Test was carried out in 100 kN capacity servo controlled Universal Testing Machine and the results are presented in Table 2.

3. Results

From the experimental results presented in Table 2, the following inferences were obtained:

(1) If the bonding temperature was lower than 375 °C, then no bonding was occurred between AZ80 magnesium alloy and AA6061 aluminium alloy and this was due to the insufficient temperature to cause diffusion of atoms (Fig. 4a).

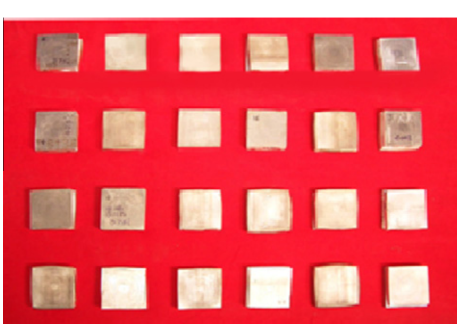


Fig. 2. Some of the fabricated diffusion bonds.

(2) If the bonding temperature was greater than 450 °C, then the bonding pressure decreased automatically after few minutes and this was due to the melting of AZ80 magnesium alloy due to higher temperature (Fig. 4b).

(3) If the bonding pressure was lower than 5 MPa, then no bonding was occurred and this was due to less number of contacting points (between surface asperities) through which diffusion of atoms generally should occur (Fig. 4c).

Table 2
Experimental conditions and lap shear strength results.

Joint no.	Bonding temperature (°C)	Bonding pressure (MPa)	Holding time (min)	Bonding (Yes or No)	Shear strength (MPa)
1	350	10	15	No	–
2	375	2	15	No	–
3	375	5	5	No	–
4	375	5	15	No	–
5	375	5	35	Yes	10
6	375	5	60	Yes	16
7	375	5	120	No	–
8	375	10	30	Yes	28
9	375	10	60	Yes	20
10	375	15	30	Yes	18
11	375	15	60	Yes	24
12	375	20	15	No	–
13	400	5	20	Yes	26
14	400	5	60	No	–
15	400	10	15	Yes	22
16	400	10	30	Yes	28
17	400	15	10	Yes	32
18	400	15	30	Yes	34
19	400	20	15	No	–
20	400	20	60	No	–
21	425	2	15	No	–
22	425	5	5	No	–
23	425	5	15	Yes	30
24	425	5	20	Yes	32
25	425	10	10	Yes	48
26	425	10	15	Yes	56
27	425	10	30	No	–
28	425	15	5	Yes	28
29	425	15	15	Yes	30
30	450	2	15	No	–
31	450	5	15	Yes	10
32	450	5	60	No	–
33	450	10	10	Yes	10
34	450	15	05	Yes	10
35	475	2	5	No	–

(4) If the bonding pressure was greater than 15 MPa, then the plates were deformed plastically causing reduction in thickness and bulging at the outer edges (Fig. 4d).
(5) If the holding time was less than 5 min, then no bonding was occurred and this was due to the insufficient time allowed for the diffusion reaction to take place (Fig. 4e).
(6) If the holding time was higher than 60 min, then excessive grain growth followed by melting of AZ80 magnesium alloy was observed (Figs. 4f, 7c and d).

4. Developing Temperature–Time (T–t) diagram

The bonding temperature of 375–450 °C, bonding pressure of 5–15 MPa and holding time of 5–60 min yielded diffusion bonding between AZ80 magnesium alloy and AA6061aluminum alloy. Temperature–Time (T–t) diagram was constructed, keeping bonding temperature in Y axis and holding time in X axis. At a constant bonding pressure of 5 MPa, the bonding temperature and holding time was varied to find out the processing (working) limits. Similarly, the experiments were conducted to find out the working limits for the bonding pressures of 10 MPa and 15 MPa respectively. These points were used to construct the Temperature–Time (T–t) diagram for the three bonding pressures and they are displayed in Fig. 5a–c. The selection of diffusion bonding process parameters inside the region in the Temperature–Time (T–t) diagram (Fig. 5a–c) always yielded good bonding between AZ80 magnesium alloy and AA6061 aluminium alloys and this was validated by conducting few more experiments.

From the Temperature to Time diagram the following inferences can be obtained:

If bonding pressure increases, the holding time required to get good bonds decreases, irrespective of bonding temperature. However, the bonding pressure does not have significant influence on bonding temperature. The maximum and minimum bonding temperature to get good bonds remain unaltered, irrespective of bonding pressure.

Diffusion bonding utilizing a pressing procedure depends on temperature and time. However, it needs to be based on the initial mechanical bonding. The press-bond experiments with aluminium alloys indicates that high temperature, up to 0.881 of the homologous temperature (T_h) and deformation are highly influential on bond strength [12].

5. Developing Pressure–Time (P–t) diagram

Pressure–Time (P–t) diagram was constructed, keeping bonding pressure in Y axis and holding time in X axis. At a constant bonding temperature of 375 °C the bonding pressure and holding time was varied to find out processing (working) limits. Similarly the experiments were conducted to find out the working limits for the bond-

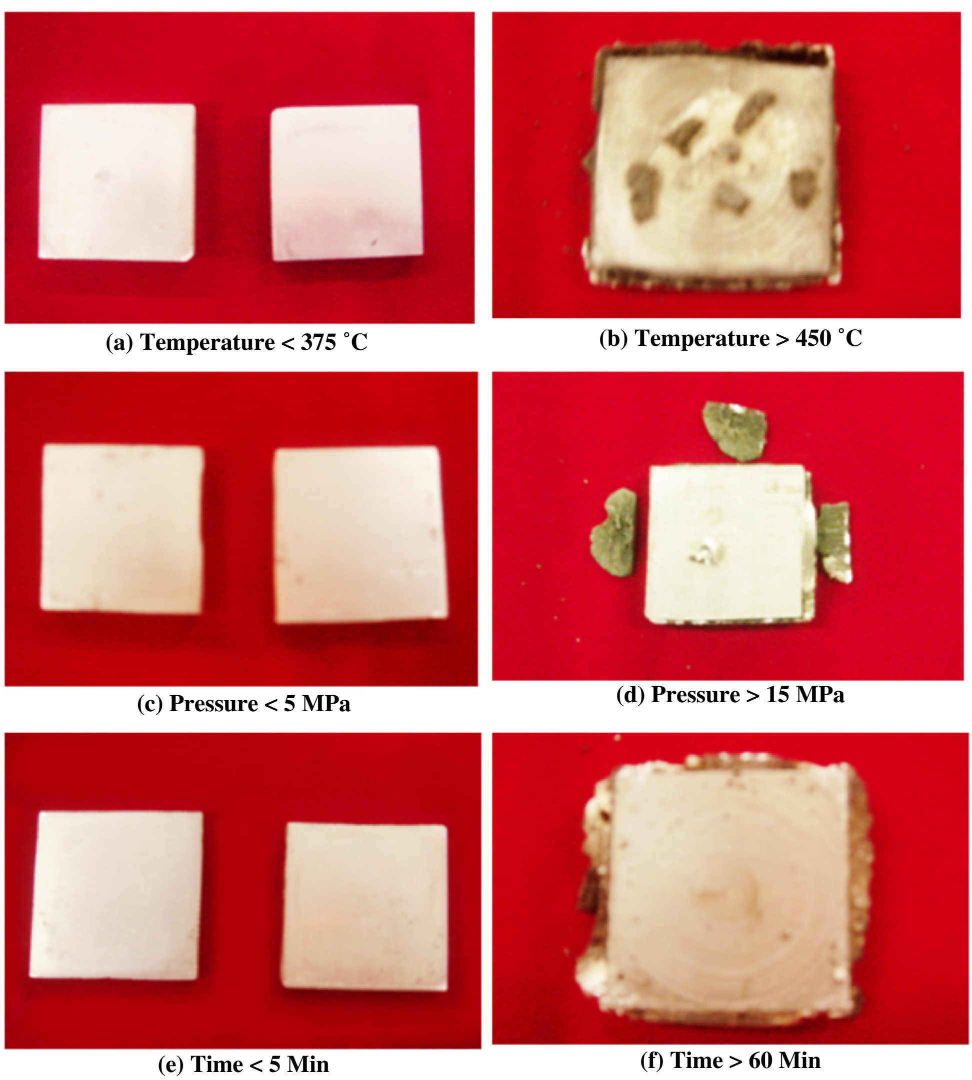


Fig. 4. Photographs of bonds fabricated using lower and upper limits of process parameters.

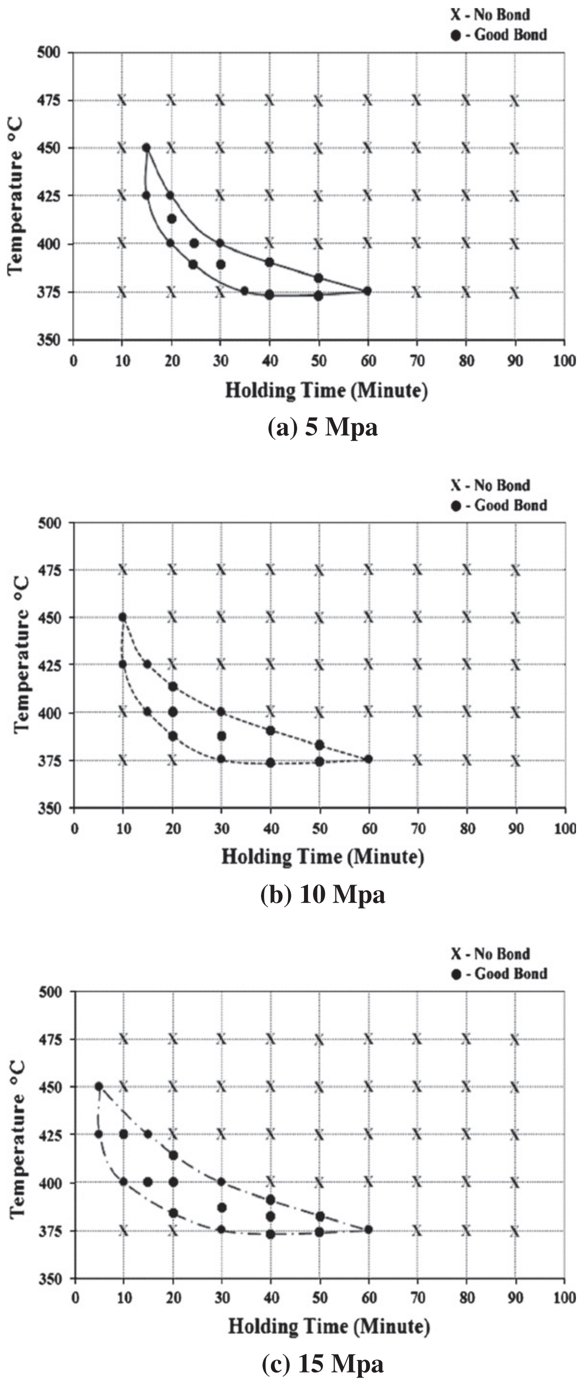


Fig. 5. Temperature–Time (T–t) diagrams.

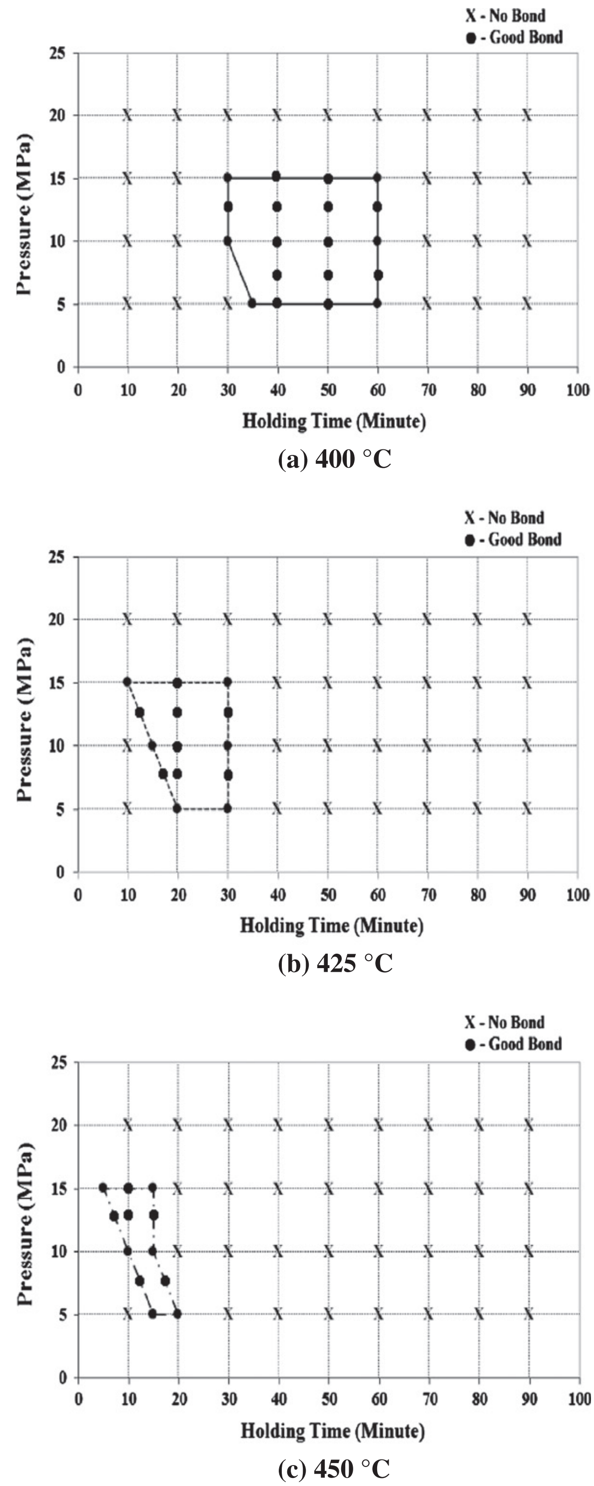


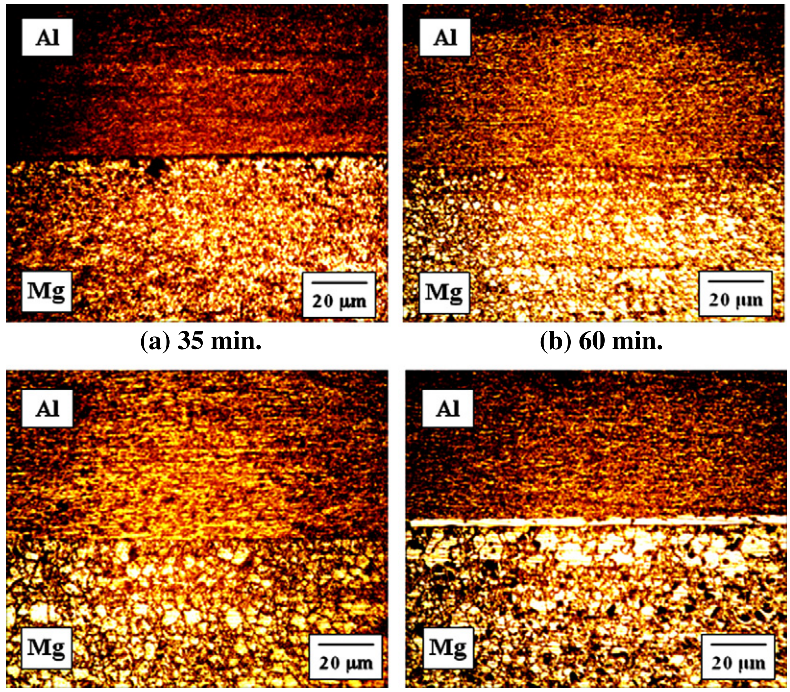
Fig. 6. Pressure–Time (P–t) diagrams.

ing temperature of 400 °C and 425 °C respectively. These points were used to construct the Pressure–Time (P–t) diagram for the three bonding temperatures and they are displayed in Fig. 6a–c. The selection of diffusion bonding process parameters inside the region in the Pressure–Time (P–t) diagram (Fig. 6a–c) always yielded good bonding between AZ80 magnesium alloy and AA6061 aluminium alloy and this was validated by conducting few more experiments.

From the Pressure to Time diagram the following inferences can be obtained:

If bonding temperature increases, the holding time required to get good bonds decreases, irrespective of bonding pressure. The processing region shifts towards Y axis and the region is narrowing down, when the bonding temperature increases. However, the bonding temperature does not have significant influence on bonding pressure. The maximum and minimum bonding pressure required to get good bonds remain unaltered.

Evren Atasoy and Nizamettin Kahraman [13] bonded pure titanium to low carbon steel using a silver interlayer. Bonding at 700 °C for 30 and 60 min of diffusion times could not be achieved. The failure of bonding at 700 °C for 30 and 60 min of diffusion times can be attributed both low temperature and insufficient time also. When the bonding temperature was increased to 750 °C with-



(a) 35 min. (b) 60 min.
(c) 90 min. (d) 120 min.

Fig. 7. Optical micrographs of the specimen bonded at 375 °C and 5 MPa for the diffusion time of: (a) 35, (b) 60, (c) 90 and (d) 120 min.

out any incremental in diffusion time, bonding could be effected. It is well known that adequate heat, diffusion time and pressure are required for atoms to diffuse in this bonding method. Diffusion time is dependent operation parameter and is interrelated with temperature, pressure and the type of bonding.

The microstructures of the joints bonded at 375 °C and 5 MPa for 35 min, 60 min, 90 min and 120 min was shown in Fig. 7. A microstructure analysis indicates that change in grain morphology is more obvious for AZ80 alloy with the increasing diffusion time than for AA6061 alloy. Equiaxed and more homogeneous grains are seen in these specimens due to absence of HAZ (heat affected zone) which exist in the fusion welding methods.

Grain growth in the bonded materials can be attributed to recrystallization and to the enveloping of small grains by bigger ones. The tendency for grain growth after recrystallization is related to grain boundary energy. In order to obtain a lower level of energy, total grain boundary per unit volume needs decreasing and this, in turn, requires the growth of grains. However, it is well known that grain growth is not desirable [14,15].

From the results, it is apparent that shear strength of the bonds depends on bonding temperature, bonding pressure and holding time. However, shear strength cannot be used to evaluate the extent of bonding because the specimens may have different tempered conditions. But it was reported [16] that the actual shear strength requirements of the bonds for aircraft structures are generally in the order of 10–20 MPa. Hence, in this investigation, the shear strength of the bonds was evaluated by conducting lap shear tensile strength. From the shear strength values, it could be inferred that all the bonds satisfy the above requirements and falls under 'good bonds' category.

6. Conclusions

- The Temperature–Time and Pressure–Time diagrams, developed in this investigation, will act as reference maps to the design engineers and welding engineers for selecting appropriate diffusion bonding process parameters to join AZ80 magnesium alloy – AA6061 aluminium alloy without trial experiments.
- A bonding temperature of 425 °C, bonding pressure of 10 MPa and holding time of 15 min yielded highest shear strength due to the formation of optimum thick diffusion layer at the interface of AZ80 magnesium alloy – AA6061 aluminium alloy.

Acknowledgements

The authors are grateful to the Center for Materials Joining and Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar, India for extending the facilities of metal joining and Material Testing to carry out this investigation.

References

[1] Sun DQ, Gu XY, Liu WH. Transient liquid phase bonding of magnesium alloy (Mg–3Al–1Zn) using aluminium interlayer. Mater Sci Eng – A 2005;A391:29–33.
[2] Hidetoshi Somekawa, Hiroyuki Watanabe, Toshiji Mukai, Kenji Higashi. Low temp diffusion bounding in a super plastic AZ31 magnesium alloy. Scripta Mater 2003;48:1249–54.
[3] Hidetoshi Somekawa, Hiroyuki Hosokawa, Hiroyuki Watanabe, Kenji Higashi. Diffusion bonding in super plastic Mg alloys. Mater Sci Eng – A 2003;A339:328–33.
[4] Yeh MS, Chuang TS. Low pressure diffusion bonding of SAE 316 stainless steel by inserting a super plastic interlayer. Scripta Metall Mater 1995;33(8):1277–81.
[5] Feng JC, Zhang BG, Qian YY, He P. Microstructure and strength of diffusion bonded joints of Ti Al base alloy to steel. Mater Charact 2002;48:401–6.
[6] Peng Liu, Yajiang Li, Geng Haoran, Wang Juan. Investigation of interfacial structure of Mg/Al vacuum diffusion – bonded joint. Vacuum 2006;80:395–9.
[7] Yajiang Li, Peng Liu, Juan Wang, Haijun Ma. XRD and SEM analysis near the diffusion bonding interface of Mg/Al dissimilar materials. Vacuum 2008;82:15–9.
[8] Peng Liu, Yajiang Li, Geng Haoran, Wang Juan. A study of phase constitution near the interface of Mg/Al vacuum diffusion bonding. Mater Lett 2005;59:2001–5.

[9] Huang Y, Humphreys FJ, Ridley N, Wang ZC. Diffusion bonding of hot rolled 7075 aluminium alloy. Mater Sci Technol 1988;14:405–10.
[10] Mahendran G, Balasubramanian V, Senthilvelan T. Developing diffusion bonding windows for joining AZ31B magnesium–AA2024 aluminium alloys. Mater Des 2009;30:1240–4.
[11] Zhao LM, Zhang ZD. Effect of Zn alloy interlayer on interface microstructure and strength of diffusion-bonded Mg–Al joints. Scripta Mater 2008;58:283–6.
[12] Horng-Yu Wu, Shyong Lee, Jian-Yih Wang. Solid-state bonding of iron-based alloys, steel–brass, and aluminum alloys. Mater Process Technol 1998;75:173–9.
[13] Evren Atasoy, Nizamettin Kahraman. Diffusion bonding of commercially pure titanium to low carbon steel using a silver interlayer. Mater Charact 2008;59:1481–90.
[14] Smith WF. Principles of materials science and engineering. 2nd ed. New York: McGraw-Hill; 1990. p. 290–296.
[15] Askeland RD. The science and engineering of materials. 3rd ed. Boston: PWS publishing Company; 1994, p. 110–127.
[16] Pilling J, Rediely N. Solid state bonding of superplastic AA7475. Mater Sci Technol 1987;3:353–9.